

APPLICATION
FOR
UNITED STATES LETTERS PATENT

TITLE: FIXED SATELLITE CONSTELLATION SYSTEM
EMPLOYING NON-GEOSTATIONARY SATELLITES IN
SUB-GEOSYNCHRONOUS ELLIPTICAL ORBITS WITH
COMMON GROUND TRACKS

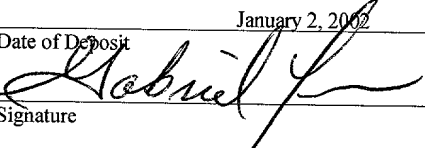
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The present disclosure describes an array of non-geostationary satellites in sub-geosynchronous, inclined elliptical orbits. Each of the satellites communicates with a

Summary

point on the earth. At least a plurality of the satellites is in an elliptical orbit with the earth at one focus of the ellipse.

At and near their apogee points, the satellites move slowly relative to the Earth. These satellites appear virtually geostationary to users within at least part of the desired coverage area.

The disclosed embodiments use three sub-constellations, each with 5 satellites. Three total sub-constellations are used. Two of these sub-constellations are used for Northern Hemisphere operation. A third constellation is for Southern Hemisphere operation. The satellites are active over only part of their total time of their orbits. The active time of the orbit is when the satellites are closest to their apogees.

These active times can occur when the satellites are at latitudes above 45°. These satellites are hence seen at high elevations over much of their primary service areas.

This system is also effectively transparent to the geostationary fixed satellite services and can be separated from the geostationary arc preferably by at least 40° at all times within the service area of the system.

Brief Description of the Drawings

Fig. 1 shows a basic layout of the multiple elliptical orbits of the present invention;

Fig. 1A shows a graphical depiction of the satellite's angular motion along its orbit as a function of the semi-major axis of the elliptical orbit.

Figs. 2A & 2B shows a block diagram of the satellite communication equipment used according to the present invention;

Fig 2C shows a flowchart of operation of the satellites of the present invention;

Fig. 3 shows the characteristics of a basic ellipse;

Figs. 4A-4F show characteristics of the three-satellite orbit of the present invention;

Fig. 4G shows characteristics of this orbit which prevent interference with geosynchronous satellites in an inclined orbit;

Fig. 4H shows characteristics of this orbit which prevent interference with geosynchronous satellites in an equatorial orbit;

Figs. 5A-5E show characteristics of the five satellite orbit of the present invention;

Fig. 6 shows an overall view of the ten satellite orbit of the present invention;

Figs. 7A-7G show the positions of the satellites of the ten satellite embodiment within their repeating ground tracks;

Fig. 8 shows the operating elevation angles for the ten satellite orbit, and their angular isolation from geo satellites; and

Fig. 9 shows ground tracks of the preferred orbits.

Description of the Preferred Embodiments

The disclosed system defines a communication system including ground communication equipment and a special constellation of satellites in elliptical orbits at lower altitudes than those necessary for geosynchronous, which simulate the characteristics of a geosynchronous orbit from the viewpoint of the ground communication equipment on the earth. The inventors recognized that satellites which orbit in certain elliptical orbits spend most of their time near the apogees of their orbits: the time when they are most distant from the earth. These satellites spend only a minority of their time near their perigee. For example, an elliptical satellite in a 12-hour orbit

spends eight of those hours near its apogee. By appropriately choosing characteristics of the satellite orbit, the satellite can be made to orbit, during that time, at a velocity that approximates the rotational velocity of the earth. The disclosed system defines a communication system using a constellation of satellites chosen and operating such that a desired point on the earth always tracks and communicates with a satellite at or near apogee.

Another important feature of the disclosed system is the recognition of how this mode of operation of the satellite changes its power characteristics. Geosynchronous satellites are used virtually 100% of the time (except when in eclipse) and hence their power supplies must be capable of full-time powering. This means, for example, if the satellite requires 5 Kw to operate, then the power supply and solar cells must be capable of supplying a continuous 5 Kw of power. The satellites of the disclosed system, however, are not used 100% of the time. During the perigee portions of the satellite orbit, the satellites are typically not using most of their transmit and receive capability and hence, the inventors recognized, do not use a large part of their power capability.

The inventors of the disclosed system recognized this feature of the satellites, and realized that the satellites could be storing the power that is being produced during this time of non-use. Therefore, the inventors realized that the size of the power supply could be reduced by a factor of the percentage of time that the satellite is not used.

The power sources can be any known means, including solar cells, nuclear reactors, or the like. If the satellite is used half the time, then the power source need only be sized to provide half the power. At times when the satellite is not being used, the power source provides power to a battery storage cell, which holds the power in reserve for times when the satellite is being used.

Like geo systems, the satellite of the disclosed system is virtually continuously in the same location. Unlike geo-based systems, however, the ground communication equipment of the disclosed system does not always communicate with the same satellite. The satellites move slightly relative to the earth, i.e. they are not always precisely at the same point in their apogees. One important advantage of the disclosed system is that the one satellite at apogee later moves to perigee, and still

later to apogees at other locations overlying other continents and areas. Hence, that same satellite can later communicate with those other areas. Therefore, this system allows a store-and-dump type system. The information can be stored on board the satellite and later re-transmitted when the satellite overlies those other areas. This system also allows all the satellites in the array to communicate with the other satellites in the constellation, through intersatellite links. This feature is desirable for real time communications.

This system has a number of other distinct advantages. Importantly, the system operation allows selecting specific geographic locations to be preferentially covered; for example, continents can be followed by the constellation to the exclusion of other areas, e.g. ocean areas between the continents. The communication equipment on the continent always communicates with one satellite at apogee, although not always the same satellite. From the point of view of the ground station, the satellite appears to hover over the ground.

This satellite system operates virtually like a geosynchronous satellite system. Importantly, these satellites according to the disclosed system orbit at about half the

altitude of the geo systems. A geo orbit orbits at 36,000 miles
altitude: the virtual geo satellite orbits at average altitudes
of 16-18,000 miles. Also, geo satellites require "apogee
motors", to boost them from their original orbits into the final
5 geo orbit. These apogee motors can double the weight of the
satellite.

This yields a communications system which costs less dollars
per launch capability because of the reduced weight to boost and
less size. Also, since the geo satellites orbit at a higher
10 altitude, they operate at a higher power, and use a larger
illuminating antenna, all other conditions on the ground being
equal. These satellites also have a much larger overall size.
This size of the satellites increases as the square of the
distance. Therefore, the geo satellite needs to be at least
15 twice as large and twice as powerful as a low altitude satellite.
The power supply conservation techniques of the disclosed system
allow the satellite to be made even smaller.

The system also provides satellites with very high elevation
angles. Maximizing the elevation angle prevents interference
20 with existing satellites such as true geosynchronous satellites.

This is another feature of the disclosed system which allows these satellites to operate in ways which avoid any possibility of interference with the geo band.

Another objective and important feature of the disclosed system is its ability to re-use satellite communication channels. Regulatory agencies such as the FCC allocate frequency bands by allocating a specific frequency band for a specific purpose. The geo satellites, for example, receive an assignment of a frequency band. Thereafter, the regulatory agency will consider that other satellites located in the same orbital position can not use this frequency because of possibility of interference. Hence, frequencies in adjacent bands which might interfere with that assigned band will not be allocated for new satellite use. With the disclosed system, there is a large angular separation between the geo-sats and those covered by the invention. Thus, the same frequencies ca be allocated anew. Another feature of the disclosed system is the location of the earth stations and satellites in a way which prevents interference with the geo bands. Specifically, the disclosed system defines embodiments using both inclined orbits and non-inclined (equatorial) orbits. The inclined orbit embodiment of the disclosed system only

communicates with the ground stations when a line drawn between the ground station and current position of the satellite will not intersect any point within x° of the ring of geosynchronous satellites, where x is the required separation between the communication for geo satellites and the communication for the satellites of the disclosed system. During other times, the equatorial component of the communication is shut off. The satellite only communicates when it is near apogee. During those times, the rotational velocity of the satellite approximates the rotational velocity of the earth, and hence the satellite tends to hang overhead relative to the earth.

For non-inclined (equatorial) orbits, the ground stations are placed in a position such that the communication does not intersect the ring of equatorial orbits, by ensuring that satellite apogees are at lower altitudes than apogees of geostationary satellites.

The system is controlled by on-board processor 280, which determines the position in the orbit and the steering of the antenna from various parameters. Processor 280 carries out the flowchart shown in Figure 2a which will be described herein.

The overall system is powered by power supply 290 which supplies power to all of the various components and circuitry which require such power. Power supply 290 includes a source of power, here shown as a solar array 292, and an energy storage element here shown as a battery array 294. Importantly, according to the disclosed system, the solar array 292 is sized to provide only some amount of power less than that required to power the satellite communication. The amount by which the solar array can be less is called herein the power ratio of the device. The power ratio depends on the kind of orbit that the satellite will have, and how long the satellite will be transmitting during each elliptical orbit. The preferred power ratio is 0.5: this will power a satellite which is communicating half the time, and the other half the transmitter and receiver on board the satellite is off and the solar array is providing power to charge battery 294.

The flowchart of operation is shown in Figure 2a. Step 350 represents controlling the antenna. This requires that the processor keep track of the satellite's position in the orbit. Step 352 determines if the satellite is in a position in its orbit where it is active (transmitting and/or receiving). If so,

flow passes to step 354 where power is drawn from power supply and the battery. If the satellite is not powered, then power is used to charge the battery at step 356.

The system also allows selective expansion of the
5 communications coverage by adding additional satellites into additional elliptical orbits.

The virtual geo satellite system of the disclosed system also enables complete communications coverage of the earth without requiring a ground network. The same satellite services
10 all different portions of the earth at different times of day. The coverage of the earth repeats over a 24 hour period. A preferred embodiment receives information relayed from the ground, relays it to the earth area below it, then stores the information, and later reads back the stored information to re-
15 transmit that same information to other areas of the earth. The system of the disclosed system increases the satellite coverage at high density geographic locations using fewer satellites than was possible with previous constellations by fixing the satellite apogee passages over given geographic regions defined by both
20 longitude and latitude.

Integral values for mean motion of the satellites in the array ensures that the ground track repeats on a daily basis. The ground tracks preferably repeat each day so that the orbit apogee passes in the same location relative to the geographic target area. This system maximizes the time of coverage and elevation angles for that pass.

Before describing the minimum satellite arrangement according to the disclosed system, the nomenclature used herein to describe the characteristics of satellite orbits will be first described. The "mean motion" is a value indicating the number of complete revolutions per day that a satellite makes. If this number is an integer, then the number of revolutions each day is uniform. This means that the ground tracks of the satellites repeat each day: each ground track for each day overrides previous tracks from the preceding day.

Mean motion (n) is conventionally defined as the hours in a day (24) divided by the hours that it takes a satellite to complete a single orbit. For example, a satellite that completes an orbit every three hours ("a 3-hour satellite") has a mean motion of 8.

The "elevation angle" δ is the angle from the observer's horizon up to the satellite. A satellite on the horizon would have 0° elevation while a satellite directly overhead would have 90° elevation. Geo satellites orbit near the equator, and usually have a $20\text{-}30^\circ$ elevation angle from points in the United States.

The "inclination" I is the angle between the orbital plane of the satellite and the equatorial plane. Prograde orbit satellites orbit in the same orbital sense (clockwise or counter-clockwise) as the earth. For prograde orbits, inclination lies between 0° and 90° . Satellites in retrograde orbits rotate in the opposite orbital sense relative to the earth, so for retrograde orbits the inclination lies between 90° and 180° .

The "critical inclination" for an elliptical orbit is the planar inclination that results in zero apsidal rotation rate. This results in a stable elliptical orbit whose apogee always stays at the same latitude in the same hemisphere. Two inclination values satisfy this condition: 63.435° for prograde orbits or its supplement 116.565° for retrograde orbits.

The "ascending node" is the point on the equator where the satellite passes from the southern hemisphere into the northern

hemisphere. The right ascension of the ascending node ("RAAN") is the angle measured eastward in the plane of the equator from a fixed inertial axis in space (the vernal equinox) to the ascending node.

5 The "argument of perigee" is a value that indicates the position where orbital perigee occurs. When using equatorial orbits, 0° argument of perigee is used for all the orbits. Inclined orbit arrays use non-zero arguments of perigee. Arguments of perigee between 0° and 180° locate the position of perigee in the northern hemisphere and hence concentrate the coverage in the southern hemisphere. Conversely, arguments of perigee between 180° and 360° locate the perigees to the southern hemisphere and hence concentrate the coverage on the northern hemisphere.

15 An embodiment of the disclosed system evenly spaces the axes of the ellipses. The spacing between RAANs is called "S" and calculated by $S = 360/n = 120^\circ$.

The disclosed system positions the satellite coverage based on both longitude and latitude of the desired continental area to be covered by the orbit. This is done, first, by synchronizing the orbit apogee to pass over the targeted geographical region

for each successive satellite. We select a suitable value for the mean anomaly, which is a fictitious angle relating to the elapsed time in orbit. 360° represents the completion of the orbit. In this example, the mean anomalies are also $S = 120^\circ$ apart.

This "mean anomaly" M relates the amount of time it takes the satellite to rotate S° around the earth (here 120°). The mean anomaly required for the 12-hour satellites to rotate to S° is 8 hours; two-thirds of a period. This corresponds roughly to the amount of time the satellite remains in apogee.

Taking the initial satellite near apogee, therefore, (180° mean anomaly) the next satellite should be backed up by 240° . This means that after 8 hours that satellite will be at 180° . Since 180° minus 240° is negative 60° which equals 300° , this is the value of mean anomaly M for satellite number 2. This system is used to select values for the constellation in a similar manner for each succeeding satellite.

Arrays with more satellites ("higher order arrays") can also be made using the same rules as those discussed above.

Successively larger numbers of satellites can be used to provide more coverage, more overlapping coverage, or smaller integral

mean motion values. As the values of M get larger, the eccentricity of the ellipses become smaller. This is because the perigee altitude is fixed at about 500 km to avoid re-entry and decay into the earth's atmosphere; longer periods have higher apogee altitudes greater supportable eccentricities.

Figure 1A shows how the satellite ellipse is selected to have an angular rate in the plane of the equator, at apogee, which approximates the angular rate of the earth. The dotted line in Figure 1A represents the angular rate of a geo satellite, and hence at this angular rate a satellite would approximate the angular speed of the earth. The ellipse is selected to have a semi-major axis length to set the minimum angular rate of the satellite at apogee. At apogee, the satellite angular rate should approximate the rotational velocity of the earth. In reality, this rotational velocity will be either a little faster or a little slower than the earth. At this time, therefore, the satellite appears to hang relative to the earth.

All elliptical orbits, including those described herein, are also subject to effects of long-term perturbations. If effects of these long term perturbations are not compensated, this could cause continental coverage to drift with the passage of time.

These perturbation effects are mainly effects from the Earth's J2 rotation harmonic. The earth is not a perfect sphere; it actually bulges at the equator. This causes gravitational effects on objects which orbit the earth. For posigrade orbits (i > 90°) the line of nodes will regress. For inclinations greater than critical (63.4° > i > 116.6), the line between the perigee and apogee (line of apsides) will regress; for other inclinations, I < 63.4° or I > 116.6, the line of apsides will progress. Exactly at the critical angles I = 63.4 or I = 116.6, the line of apsides will remain stable a very desirable feature in maintaining apogee at a certain latitude. In the equatorial plane, the combined effect of these two major perturbations cause the apogee to advance or move counter-clockwise from the sense of looking down from the celestial north pole. All of the satellites in a given array design would be affected similarly. Fortunately, this effect could be compensated by slightly increasing the period of each satellite in the array by an amount which offsets the J2 perturbation. This affects the system by causing a point on the earth to take a slightly longer time to reach the satellite's next apogee arrival point. This effect is

compensated by slightly increasing the satellite's period. The advance of perigee is suppressed by setting the inclination at one of the critical values.

A first embodiment of the invention uses $N=3$ satellites, where N is the total number of satellites, preferably in the equatorial plane, to cover $N - 1 = 2$ continents. The rules for spacing and phasing the satellites will be given in the general form that can be used later for more complicated constellations or arrays.

The mean motion integer sets the minimum number of satellites in the array and n_c the number of continents that are followed. Here $n_c = 2$ provides a satellite period equal to 12 sidereal hours. N (the minimum number of elliptic satellites in the array) is determined by using the relationship $N = n_c + 1$.

Thus, $N = 3$. This is the minimum number of satellites that need to be in the array; we can also set the number of satellites in the array N to be any integer greater than $n+1$.

The apogee passage is synchronized over the targeted geographical region, for each successive satellite, moving counterclockwise as viewed from the celestial North Pole. This

is accomplished by selecting a suitable value for the mean anomaly.

Refinements: Additional features augmenting the usefulness of the above simpler version include:

5 1) Inclining the elliptical orbital planes at the critical inclination angles (63.435 or 116.535°), with phasing to maintain a single repeating ground track. The single repeating ground track for the simplified non-inclined example above is simply the line of the equator.

10 2) Taking advantage of the higher apogees in allowing more direct cross-linking between satellites than with present low-altitude circular arrays. Usually, a single cross-link suffices, even when the longitude difference between end points is 180° (on the opposite side of the earth).

15 3) Placement of apogees over a selected latitude and longitude for optimal coverage of a potential market area. This is done through proper selection of all the orbital parameters, with particular attention given to selection of argument of perigee, ω .

20 First Embodiment

The orbits of the disclosed system are shown in Figure 1. The satellite 100 is shown in an elliptical orbit 102 around the earth. The communication equipment on the satellite 100 communicates with earth ground station 104, and also beams the information to earth ground station 106. Satellite 110 is shown in a separate independent elliptical orbit communicating with ground stations 112 and 114 on the earth. Note also that the satellite 100 can communicate directly to the satellite 110 via communication link 120.

The preferred characteristics of these orbits are described in Table I.

TABLE I

Satellite No.	P1	P2	P3
Semi-Major Axis, a =	26553.98km	26553.98km	26553.98km
Inclination, I =	0 deg	0 deg	0 deg
Arg. Perigee, w =	270 deg	270 deg	270 deg
Eccentricity, e =	0.51	0.51	0.51
Rt. Ascension, RAAN=	0 deg	120 deg	240 deg
Mean Anomaly, MA =	180 deg	300 deg	60 deg

Satellite 100 also includes store and dump hardware thereon as described herein. This allows the satellite to

obtain program information so that later in its orbit, when at the position 130, it can send its same information to ground station 132.

A detailed block diagram of the electronics in the satellite is shown in Figure 2. This block diagram shows elements which carry out communication between the ground station 104, the satellite 100, and the remote user station 106. The inter-satellite links 120 are shown from the satellite 100 to the satellite 110.

The video input to be distributed is received as video input 200, and input to a video coder 202 which produces digital coded video information. This digital coded video is multiplexed with a number of other channels of video information by video multiplexer 204. The resultant multiplexed video 206 is modulated and appropriately coded by element 208 and then up-converted by transmitter element 210. The up-converted signal is transmitted in the Ku band, at around 14 GHz, by antenna 212. Antenna 212 is pointed at the satellite 100 and received by the satellite's receive phased array antenna 214. Antenna 212 is controlled by pointing servos 213.

The received signal is detected by receiver 216, from which it is input to multiplexer 218. Multiplexer 218 also receives information from the inter-satellite transponders 240.

5 The output of multiplexer 218 feeds the direct transponders 250, which through a power amplifier 252 and multiplexer 254 feeds beam former 256. Beam former 256 drives a transmit, steerable phased-array antenna 260 which transmits a signal in a current geo frequency band to antenna 262 in the remote user terminal 106. This signal preferably uses the same frequency that is used by current geo satellites. The phased array antenna is steered by an on-board computer which follows a pre-set and repeating path, or from the ground. This information is received by receiver 264, demodulated at 10 266, and decoded at 268 to produce the video output 270.

15 The satellite includes another input to the multiplexer from the steerable antenna, via the intersatellite link 120 and receiver 240. Transmit information for the the intersatellite link is multiplexed at 242 and amplified at 246 20 prior to being multiplexed.

Output 222 of input multiplexer represents a storage output. The satellite electronics include the capability to store one hour of TV program information. The TV channels typically produce information at the rate of 6 megabytes per second. The channels are typically digitally multiplexed to produce information on 4-6 channels at a time. Therefore, the disclosed system preferably uses 22 gigabytes of storage to store over 1 hour of information at about 4.7 megabytes per second. The information stored will be broadcast over the next continent.

The storage unit 224, accordingly, is a wide SCSI-2 device capable of receiving 4.7 megabytes per second and storing 22 GB.

Upon appropriate satellite command, the output of the storage unit is modulated and up-converted at 226.

This basic system shown in Fig. 2 can be used in one of the preferred satellite arrays of the disclosed system. These arrays will be discussed herein with reference to the accompanying drawings which show the characteristics of these satellite arrays.

This first embodiment uses a simplified 12-hour equatorial plane satellite array $n=2$, $N=3$. The mean motion n of 2 means that each satellite completes an orbit around the earth twice per day.

5 An important enhancement of an $N=3$ case is obtained by modifying the characteristics of the orbits so that the satellites coalesce over the covered areas at the moments when satellite coverage changes. The term coalesce as used herein means that as one satellite moves out of range of the ground tracking, the next satellite moves into range at that same position. In fact, the two satellites come very close to one another at that point -- within 1° from the view of the satellite. This simplifies the ground tracking, since the switchover between satellites does not require much antenna movement.

15 Figures 4A-4F show the basic three-satellite "rosette" formed by the three elliptical orbits. The earth 300 is located at one of the foci of each of the three ellipses of the respective satellites. Satellite 302 communicates with point 304 on the earth. Satellite 302 orbits the earth in ellipse 306. The satellites 1, 2 and 3 respectively have

ascending nodes of 0, 120 and 240, and respectively have mean anomalies of 180, 300, and 60.

Similarly, satellite 310 orbits the earth in ellipse 312, and satellite 320 orbits the earth in ellipse 322. Satellites 310 and 320 are both in a position to provide coverage to the second covered continent area 314. Note that satellites 310 and 320 are in their coalesced position -- they are very close positionally, to one another. Satellite 320 is moving away from apogee while satellite 310 is moving toward apogee. The tracking antenna is hence commanded to switch between tracked satellites at the time when satellites 310 and 320 are positionally very close , but having adequate angular separation to avoid self-interference. According to the disclosed system, this switchover occurs when the satellites are within 5° of each other.

The satellites all orbit in a counter-clockwise direction relative to the sense shown in Figure 4. The earth also orbits in the counter-clockwise direction. The semi-major axes of the ellipses in Figure 4 are shown as axes 308, 314, and 316, respectively.

In order to describe these orbits, first the characteristics of an ellipse will be described. Figure 3 shows ellipse 400, having a focus 402. The satellite orbits along the path of the ellipse 400, with the center of the earth being at the focus position 402 ("the occupied focus").

The apogee 404 and the perigee 406 of the orbits are defined by the points on the ellipse which are farthest from and closest to the focus of the ellipse, respectively. The amount of difference between these distances define the eccentricity of the ellipse. The semi-major axis 408 is defined as half of the long axis of the ellipse. This semi-major axis runs through the two foci of the ellipse, to split the ellipse into two halves. The two lengths along the semi-major axis, from one edge of the ellipse to the occupied focus of the ellipse are called the "radius of perigee" and the "radius of apogee"; the latter being the longer.

As the eccentricity of an ellipse approaches zero, the ellipse becomes less elliptical, eventually approaching a circle ($e=0$) when the eccentricity is zero. The semi-major axis of a circle is the radius of the circle.

The characteristics of the ellipse/ object in elliptical orbit are calculated as follows.

The apogee, $r_a = a \cdot (1 + ECC)$.

Perigee $r_p = a \cdot (1 - ECC)$.

5 A more eccentric ellipse (higher value of eccentricity ECC) has a greater difference between the values P and R. Hence, such an ellipse is less like a circle. The characteristics of the ellipse are therefore determined as a function of its eccentricity.

10 The position of a satellite in orbit follows Kepler's laws of motion which states that the orbiting element will sweep out equal areas of the orbit in equal times. This results in the satellite moving very rapidly when it is at an approaching perigee, but very slowly when it reaches apogee.

15 For a twelve hour elliptical orbit, therefore, it can be seen that the satellite will spend most of its time near apogee.

The numbers on the ellipse of figure 3 represent time indications of hours passed in a 12 hour orbit, e.g., they indicate the number of hours since zero that have elapsed in a
20 12 hour orbit.

The preferred ellipse for the 3-satellite elliptical orbit has an eccentricity of about 0.51. This value best allows the satellites to coalesce.

The earth rotates once in every 24 hour period, and hence takes eight hours to rotate between the major axes of the three equally spaced ellipses (120° spacing). Figure 4A shows the point to be covered 304 is initially pointing directly towards satellite 302 which is at apogee at time 0:00. As time passes, both the satellite 302 and the earth will rotate.

As time passes, the satellites move from the position shown in Fig. 4A. Fig. 4B shows the position one hour later at time 1:00. Satellite P1 has moved away from apogee, although it has moved relatively little. Satellite P2, on the other hand, is now moving much more rapidly at this time, since it is approaching perigee, while P3 is still near the apogee position.

An observer on or near the equator sees the nearest satellite appear to climb in altitude from almost directly overhead, towards apogee, all the while staying almost directly overhead at an elevation angle of $80-90^\circ$. The

satellite is actually rotating more slowly than the earth during this time: it is appearing to move from east to west, rather than west to east as most low or medium altitude satellites move in the sky.

5 Fig. 4C shows a view of the satellites one hour later at time 2:00. The tracked locations 304 and 314 each still view a satellite near its apogee position. Satellite P3 continues to move towards apogee and hence appears to hang overhead. P1 is still around apogee and thus also appears to hover.

10 Fig. 4D shows yet another hour later at time 3:00. P3 is still at apogee, but P1 is approaching perigee. Notice that P2 is coming out of perigee and approaching the coalescence point at which P1 and P3 will cross paths. That crossing of paths is shown in Figure 4E, time 4:00, when P1 and P2 have
15 coalesced in their positions at the time when point 304 switches over between coverage by satellite P1 and P2. At that time, the satellites are within 1° of one another as viewed from the ground.

20 The above has described the satellite P1 moving from directly overhead the point to be covered, to the point where satellite P1 no longer covers the point to be covered.

Therefore, the satellite is transmitting for eight of the twelve hours of its orbit; $2/3$ of the time.

This cycle repeats. As the satellites continue to orbit, different satellites take similar positions to those shown in Figs. 4A-4E. Fig. 4F shows the cycle starting to repeat with satellite P2 moving toward apogee, satellite P1 moving toward perigee, and P3 hovering relative to the earth near its apogee.

Figures 4A-4F demonstrate the important features recognized by the inventors of the disclosed system, whereby the satellites spend most of their time at apogee. At the highest points of apogee, the velocity of the satellite very nearly matches that of the earth, and so the satellite appears to hang overhead. The satellite is preferably tracked while its angular velocity differs from the earth's angular velocity by 20% or less.

Importantly, the covered areas on the earth always see either a satellite directly overhead or two satellites which are very nearly directly overhead. Figures 4A-4F show how this system actually appears to the communications point 304 to be virtually geosynchronous. The communications point

communicates with different satellites at different times in the satellite orbit. The communications point is always communicating with one satellite.

5 The satellites follow repeating ground tracks, since the cycle of satellite movement shown in Figures 4A-4F continually repeats. Importantly, this allows the ground tracking antenna 212 to continually follow the same path, starting at a beginning point, tracking the satellite, and ending at the coalesce point. After the satellites coalesce as shown in Figure 4A, the antenna begins its tracking cycle.

10 The inventors of the disclosed system have optimized this system for preventing interference with geo satellites.

Specifically, consider Figure 4G which shows a multiplicity of satellites in inclined elliptical orbits. The disclosed system preferably operates to monitor satellites at 15 and near their apogee positions. The satellites near perigee are moving too rapidly, and hence are not tracked. More generally, the system of the disclosed system operates such that the satellites are only being used at certain times 20 during their orbits. In this embodiment, those certain times are when the satellites are at apogee. Non geosynchronous

circular arrays are commonly used at present; they are actually much less efficient, since with zero eccentricity they spend a significantly greater time on the side of the earth away from the populated continents. The arrays of the disclosed system, on the other hand, spend most of the time at or near apogee over the populated continents of interest, and a relatively small time (at high angular velocities) passing through perigee in regions of no commercial interest.

The satellites are only used when their geometry is such that there is no possibility of the line of sight between the ground station and the satellite interfering with the geosynchronous band of satellites. This allows the satellite communication to take place on the same communication frequency band normally assigned to geosynchronous satellites.

Moreover, the disclosed system teaches that when the satellites are not communicating, either because the satellites are no longer at their tracked apogee portion and/or when the satellites are in a region where they might interfere with geosynchronous satellites, the main transmission is turned off. During this time, the power supply is used to charge the battery. This means that the

power supply can be made smaller by some factor related to the duty cycle of the satellite.

Another consideration is since the satellites only communicate while near apogee, they are never eclipsed by the earth. The satellites can always receive sunlight for solar operation while transmitting and receiving.

For example, Figure 4G shows satellites in orbit. In the example given in Figure 4G, the satellites are only tracked when they are in the position of the orbit above the line 450. The only possibility of interference with geo satellites comes when the tracking beam is within 10° to 30° of the geo band. So long as an angular separation greater than this amount is maintained, there can be no interference. Therefore, the disclosed system allows re-using the frequency bands which are usually assigned to geosynchronous satellites in a position where interference with the existing satellites can not occur.

The same rules are used to construct higher order arrays with successively larger integer mean motions and hence shorter periods. These arrays require a larger number of satellites, but provide somewhat better coverage of the earth.

Since more satellites are used in these higher order arrays, each satellite need spend a lesser amount of its time at apogee. This allows orbits to be formed wherein the values of eccentricity are allowed to become smaller as the mean motion increases. The ultimate limit is atmospheric drag, which limits perigee altitudes to about 500 kilometers. This would correspond to a 1500 kilometer apogee elliptical orbit with a resulting eccentricity of $(r_a - r_p) / (r_a + r_p)$ which is approximately 0.067. This described orbit is not practical since its period is about 1 hour and 45 minutes which is not an integral value for the mean motion. The next nearest value for mean motion would be $n=14$. The $n=14$ orbit, however, would be so slightly elliptic that it would not offer much advantage over the circular orbits.

Practically, those arrays having mean motions of 3, 4, 5, 6, 7 and 8 are most preferred according to the disclosed system. The most preferred orbits according to this invention include the three-satellite orbits, the four-satellite orbits, and the five-satellite orbits. A

particularly advantageous embodiment uses two arrays of five
satellite orbits.

As discussed above, all of these orbits include long-term
perturbations which would, if not compensated, cause the
5 desired continental coverage to drift off with the passage of
time. The two major perturbation effects are due to the
earth's J_2 harmonic; and include:

- Regression of the line of nodes (for posigrade orbits),
and

10 - Advance of perigee.

- For inclined orbits, the advance of perigee can be
suppressed by setting the inclination, i , at either 63.435 or
116.565°.

The combined effect of these two major perturbations in
15 the equatorial plane, due to the J_2 harmonic term has the net
effect of causing the apogee to advance in a counter-clockwise
direction looking down from the celestial North Pole.). All
the satellites in a given array design would be affected
alike. Fortunately, this effect can be compensated by
20 increasing slightly the period of each satellite in the array
in a way such that the earth takes a slightly longer time to

reach the next satellite's apogee arrival point. This is compensated by adding this extra time to the satellites' periods. The exact amount will vary, and is a function of a number of variables, including the orbital periods, inclinations, and eccentricities.

For inclined elliptic orbits (at critical inclination angles), there will be no rotation of perigee in either direction. However, there will be a regression of the line of nodes which must be compensated by a small adjustment in orbital period. This will cause the plane of the orbit to rotate clockwise in the sense looking down from the North Pole. If that happens, the satellite would pass over a selected meridian at a slightly earlier time each day (or each repeat cycle), unless we adjust the period of the satellite.

In this case, we would shorten the period of the satellite, which effectively 'stretches' out the trajectory ground trace and causes the ground track to repeat exactly over the life of the satellite.

As described above, third order effects due to tesseral terms may need to be compensated by small orbit maintenance maneuvers using minuscule amount of fuel.

The preferred four-satellite array is shown in Figures 5A-5E. This array shows four satellites used to track three continents. These satellites orbit in elliptical orbits having an eccentricity of 0.6. Figures 5B and 5D show the satellite coalescing which occurs according to this embodiment.

Figure 6 shows an overall view of the 10 satellite array; and Figures 7A-7E show the ground tracks for a satellite array with 5 satellites having a period, T, equal to 6 hours. This array is preferably used with two sets of five satellites, yielding a ten-satellite, six hour constellation.

The preferred communications system uses a ten satellite system, each having six hour orbits, and each optimized for users in the Washington, DC area. This still, however, provides coverage throughout the rest of the continental United States, and the entire northern hemisphere as well as that part of the southern hemisphere down to about 10 deg South latitude.

The system uses ten equally-spaced prograde satellite orbit planes. All satellite orbits are at the 'critical' inclination angle of 63.435° to prevent rotation of the line of apsides.

The ground track is adjusted so as to pass directly over Washington, DC by adjusting the right ascensions of all the orbits while maintaining their equal spacing. The argument of perigee is adjusted to obtain apogees over or nearly over the targeted latitude and longitude.

Fig. 6 shows an overview of the orbital constellation. It can readily be seen that the satellites favor the Northern Hemisphere by spending more time, and reaching a higher altitude in the Northern Hemisphere. Figure 6 shows a snapshot of time at 0:00 hours, and it should be seen that all satellites except for satellites P5 and P1 are over the Northern Hemisphere at that time.

Figs. 7A-7G show a Cartesian, or Mercator, plot of the world showing the repeating ground tracks. The satellite array has a repeating ground track that repeats every 24 hours. The satellites appear to 'hover' or dwell along four equally-spaced meridians, one of which is at the longitude of Washington, DC; the others being spaced at 90° intervals from Washington.

Fig. 8 shows the minimum elevation angle to the highest satellite over Washington, DC, as a function of time. Every

24 hour period has ten elevation angle peaks of satellites on
a descending (from north proceeding towards the equator) at or
near the observer's zenith (90 deg). The lower, sharper peaks
in the figure represent other satellites on ascending passes;
5 they are at lower altitudes and thus going faster. These
ascending satellites are not actively transmitting to users on
the ground at the times when they are on ascending passes.

The preferred system uses a total of ten (10) satellites
in critically-inclined ($i=63.4$ deg) 6-hour orbits, phased and
10 oriented to provide optimal earth coverage. As will be seen,
this geometry also provides a very high elevation angle, and
hence avoids interference with the existing geo communications
satellite band. The preferred orbits have apogee and perigee
altitudes of 20074 and 654 kilometers, respectively.

15 From a user's viewpoint, the satellites are accessed
sequentially at nominal 2 hour and 24 minute intervals at
exactly the same point in the northwestern sky (the 'start
point' of the tracking segment), and are tracked in a roughly
northwest to southeast trajectory to a point in the sky well
20 short of intersecting the geo band of satellites. The
satellites remain at apogee during the time while they are

being tracked from the ground. Hence, these satellites are only tracked, and communicated with, while their velocity closely matches the velocity of the earth. When the satellites begin to approach the perigee stage, and hence
5 their velocity increases relative to the earth's rotation to differ therefrom by more than 25%, for example, they are no longer being tracked by the communication equipment on the earth. At this end point of the tracking segment, the ground communications antenna is directed back to tracking its start
10 point to repeat the sequence as the next-appearing satellite is acquired. Tracking along the active arc segment is accomplished at less than 2 deg/min. For the present array, this results in every ground communications antenna effecting ten switchovers per day. As explained above with reference to
15 Figure 1, the steering operation of the disclosed system preferably uses phased array steering of the antenna. However, more-conventional antenna steering is also contemplated.

Importantly, the trajectory segments appear exactly the
20 same to the user for every satellite, since the azimuth-elevation trace is repeated for each satellite.

This system defines significant advantages. Its operating altitudes are half that of existing geo systems. This greatly reduces link margins and emitted power requirements for the satellites.

5 Apogees are placed on the meridians of longitude of the heavily-populated areas for which the constellation is optimized. Apogee points may also be adjusted to approximate the targeted area latitudes as well. The satellite tracking arcs over the targeted areas remain roughly overhead (within 10 30-40° of zenith), with slow angular movement during periods when the satellite is active. The trajectories for mid-latitude (20-50° North latitude) observers located directly under the apogee points in the high-population targeted areas are approximately north-south oriented.

15 All ten ground tracks are identical, and only the satellite that is currently covering the repeating ground tracks change. The repeat cycle is 24 hours. Since the satellites move from one geographic area to another, information once transmitted can be re-broadcast at another 20 location.

The Mercator plot of Figures 7A-7E show that the entire system actually follows one ground track, repeating after 24 hours. It actually 'folds over' from the left edge of the world map to the right edge, giving it the appearance of multiple traces.

Table II gives the orbital parameters, or ephemerides, of the entire array of ten satellites:

continued

TABLE II
SYSTEM ORBITAL PARAMETERS

Sat #	a (km)	i (deg)	e, (ecc.)	w, (deg)	RAAN (deg)	MA (deg)
1	16742	63.435	0.58	315	0	0
2	16742	63.435	0.58	315	072	072
3	16742	63.435	0.58	315	144	144
4	16742	63.435	0.58	315	216	216
5	16742	63.435	0.58	315	288	288
6	16742	63.435	0.58	315	180	0
7	16742	63.435	0.58	315	252	072
8	16742	63.435	0.58	315	324	144
9	16742	63.435	0.58	315	036	216
10	16742	63.435	0.58	315	108	288

Some adjustments will be required to account for long term orbital perturbations as described above. This

adjustment is common in satellites requiring precise repeat cycles such as Topex-Poseidon, or the Canadian Radarsat.

Similar views to those from the above can be drawn for the preferred ten-satellite array. An important point of the ten-satellite array, moreover, is that there is good inter-satellite connectivity for cross-linking.

Fig. 7A shows the position of the satellites at time 00:00. Compare this with Fig. 7B, which shows the same satellites twenty-four minutes later. The satellite P4, which is substantially over Washington, D.C., has moved very little, albeit P5 will be picking up speed as it approaches perigee. P4 appears to hang over Washington, D.C., since it is near the apogee portion of its orbit and its velocity very closely matches the velocity of the earth.

In contrast, during the same short period of time, the satellite P1, at perigee, has moved very quickly and very far along its orbit. Similarly, satellite P8 (over Europe), P5 (over Southern Africa) and P9 have moved very little. Twenty-four minutes later, Fig. 7C shows that satellite P4 has started to move away from the United States, but satellite P7 is now in place, very close to its apogee. This is evident

from its position twenty-four minutes after that, shown in Fig. 7D, where satellite P7 has moved only very little, and is still well-covering the United States. At time 1:36 shown in Fig. 7E, the satellite P7 is over Washington, D.C.

The satellite P7 is still over Washington D.C. at time 2:00 hours, shown in Fig. 7F. The satellite starts to move at time 2:24, shown in Fig. 7G.

The disclosed system intends that the satellites be used for communication during only some part of the time while they are in orbit. During other times in orbits, the satellites are not being used for communication, but instead are charging their energy storage. This feature of the invention has been described above, but will be described in more detail herein with reference to Figures 2A, 4G and 4H.

Figure 4G shows a view of the earth from, for example, the view of the satellite from the sun. This figure shows all of the satellite orbits, and their elliptical orbital paths. The geosynchronous satellites are in equatorial planes shown as the geo ring 800. Communications equipment on the earth communicates with this geo ring 800. Moreover, sometimes the geo satellites are perturbed by the earth's oblateness, hence

effectively forming orbits which are slightly inclined. The geo rings should therefore be considered at occupying a 5° position bordering their nominal position.

Ground communications equipment on the earth communicates with this geo ring. The cone of communications to the geo ring is shown as 802.

When the ground communication equipment on the earth communicates with the satellites P1-P5, it should be seen that they are aimed at a position of the sky, 804, which is completely separated from the geo ring 802. According to the disclosed system, a distance is maintained between the satellites and the geo ring 800. The angular separation θ is the minimum acceptable angular separation which can ensure no interference between the geo ring and the satellites of the disclosed system. An embodiment uses an angular separation of 30° , which is an amount which will obviate any possibility of interference problem. More generally, however, any angular separation greater than 15° would be acceptable.

Taking the satellite P3 as an example, therefore, the satellite can only be used according to the disclosed system when it is in its orbit between the points labelled 808 and

810. However, the virtual geo system which is preferably used according to the disclosed system uses these satellites during even less of their orbit, only between the points 812 and 814. When the satellite is in the other positions of its orbit, the satellite is not consuming power or transmitting. Therefore, this prevents any possibility of interference with the geo satellite systems.

The operation of the equatorial satellites is similar. The equatorial satellite array is shown in Figure 4h. The equatorial satellite is shown as satellite ring 850. If the ground station is on the equator, shown as ground station 852, then it would, at least at some times, interfere with satellites in the geo ring shown as 854. However, if the ground station is separated from the equator by at least 30° , such as shown as position 856, then at least part of the satellite ring has no chance of interference with the ring 854. Therefore, the satellite calculates geometries such as to obviate interference with the satellite ring.

Therefore, more generally, the disclosed system operates as shown in Figure 2a. The antenna is controlled at step 350, and from the antenna control the position of the satellite

relative to geo are determined at step 870. This can be determined, for example, from the pointing angle of the antenna. Step 872 determines if there is any possibility of interference between the two. This is determined from a numerical difference between the pointing angle and the position of the geo ring. If there is any possibility of interference, control passes to step 874 where the satellite communications is disabled. If interference is not possible at step 872, then the satellite is enabled at step 874. An enabled satellite can be, but is not necessarily, turned on. For example, in the virtual geo embodiments, the enabled satellite will be maintained in the "off" position during some of the time when it is enabled. Therefore, step 352 determines if the satellite is powered. This may be determined from the repeating ground track, or other information. If the satellite is not powered at step 352, the battery is charged at step 356. If the satellite is powered, then power is drawn from both the supply and the battery at step 354.

Second Embodiment

Another embodiment, also referred to herein as the "VIRGO" embodiment, uses satellite sub-constellations with prograde elliptical orbits of approximately 8 hour periods. Each of the satellites within a sub-constellation has the same ground tracks as the other satellites within the subconstellation, or repeating ground tracks.

Each sub-constellation includes several satellites in each of the individual ground tracks. The satellites are spaced such that as one satellite leaves a service area, another satellite replaces it in the same ground track.

As will be established herein, each satellite is in communication with the ground station during a portion of the trajectory where the satellite is at or near its apogee. During this time, the relative motion of the satellite, i.e. the perceived motion of the satellite relative to the Earth, is slow. The satellite travels through a relatively small angular arc, e.g., 40%, during its active phase.

As the one satellite departs from its active phase in the descending direction, the ground user can switch to the next-appearing satellite in the ascending portion of the active

phase of this next satellite. Continuity of coverage is thus provided by this switch-over.

During its active phase, each satellite is virtually geostationary. That means that it appears relatively stationary to a user on the earth.

The concept behind the virtual geostationary orbit can be illustrated with analogy to the walking juggler. A juggler's clubs cluster together and move very slowly at the highest point in their trajectories. At the low point of the trajectories, the juggler is catching and transferring the clubs hand-to-hand rapidly. At the high point of the trajectory, however, the clubs move much slower.

The satellites in a virtually geostationary constellation are intentionally placed in stable elliptical orbits with their apogees over the intended users. Like the juggler, these portions rise over the service area and appear to hang there. Additionally, each satellite is active for only a predetermined portion of its orbiting time, closest to its apogee portion. The satellites are spaced such that when one satellite in the subconstellation reaches its inactive portion, another satellite in the subconstellation becomes

active. Hence, the satellites are spaced such that one ascending satellite replaces another descending satellite leaving the service area.

Since the satellites are in 8 hour orbits, each satellite peaks three times in each 24-hour day. Each of the peaks is located to follow a populated region. Using a Northern Hemisphere apogee orbit as an example, each satellite ascends, reaches its turn on point and begins operating, goes through its peak ("apogee") and then descends. The satellite eventually reaches its turn off point. The satellite is then replaced, after its time of "hanging", by the next satellite in the array. The first satellite then falls rapidly into the Southern Hemisphere and quickly rises into the next Northern Hemisphere peak. Each satellite's peak is placed over one of the three Northern Hemisphere Continental masses each day.

In order to provide coverage to countries in the Southern Hemisphere, the embodiment employs another grouping of 5 satellites having their apogees in the Southern Hemisphere.

Each of the subconstellations is a mean motion 3 array. Each of the satellite peaks is separated from other satellite peaks by 120° of longitude ($360^\circ/3$).

The longitudes selected for apogee placement of this array are 79°W, 41°E, and 161°E longitude. These five satellites serve the populated areas of South America, South Africa, Australia and New Zealand.

Each satellite, in a single day, appears at apogee three times. This requires three satellites out of a total of five to be active at any time. Overall, each satellite must then be active 3/5 of the time over a full day, or 14.4 hours. Since this represents one day's total active time, and the satellite has been active over three geographic region, each region will be covered by a single satellite for 4.8 hours. In other words, each 8-hour satellite period, the satellite will be active for a 4.8 hour period - or 2.4 hours on either side of the apogee.

The satellites in this array have a duty cycle of 60%; that is, they are actively communicating 60% of the time. Their on/off switching times occur 2.4 hours on either side of the apogee. This corresponds to a latitude of 46°, and an altitude of 18044 km. The active phase for each satellite occurs at latitudes greater than 46° and altitudes greater than 18044 (up to and including apogee at 27288 km). The

satellites remain well clear of the GEO band, while active, so there is no possibility for electronic interference with GEO communication satellites.

Because of the operating features discussed above, VIRGO satellites operate only when the satellites are at least 40° separated from the line of sight of geo satellites. Hence, existing Ku and C frequency equipment can be used without interfering with other communication.

The elliptical planes in the two Northern Hemisphere sub-constellations are inclined at 63.4° with respect to the plane of the equator. This means that the apogees will always appear to be roughly at 63.4° North latitude.

The two 5-satellite sub-constellations are called Aurora 1 and Aurora 2. These are used to provide continuous coverage of this type. The third subconstellation is called Australis. Two or three spare satellites are placed into "parking" orbits where they can be boosted into different orbits if necessary.

The VIRGO™ orbital characteristics are as follows.

TABLE 1

VIRGO™ ORBITAL CHARACTERISTICS

	Aurora I™ Sats n=1-5	Aurora II™ Sats n=1-5	Australis™ Sats n=1-5	Spare Satellites
Semimajor Axis	20281	20281	20281	7285
Eccentricity	0.66	0.66	0.66	0.05346
Inclination	63.435	63.435	63.435	63.435
Right Ascension of the Ascending Node	341.5 53.5 125.5 197.5 269.5	255.3 327.3 39.3 111.3 183.3	52.2 124.5 196.5 268.5 340.5	0 180 30
Argument of Perigee	270 270 270 270 270	270 270 270 270 270	90 90 90 90 90	270 270 90
Mean Anomaly	0 144 288 72 216	108.2 252.2 36.2 182.2 324.2	0 144 288 72 216	0 0 0

The apogee of these VIRGO™ satellites is at 27,300 kilometers. This is approximately three-quarters the altitude of geostationary satellites. This lower altitude provides less propagation delay to orbit.

The ground tracks of this embodiment are shown in FIG. 9. These produce the following locations of VIRGO™ active arcs.

TABLE 2

LOCATIONS OF THE VIRGO™ ACTIVE ARCS

(Sub-Satellite Longitudes in Degrees East)

AURORA I™ NORTHERN HEMISPHERE	AURORA II™ NORTHERN HEMISPHERE	AUSTRALIS™ SOUTHERN HEMISPHERE
8 - 53 Europe	78 - 123 India - China	19-64 Africa
128 - 173 Japan	198 - 243 Alaska - Hawaii	139 - 184 Australia - NZ
248 - 293 Con.US	318 - 3 N. Atlantic	259 - 304 South America

... That's called back door.

... That's called back door.

TABLE 3

VIRTUAL-GEO ORBITAL ELEMENTS, PREFERRED EMBODIMENT

All Satellites: Semi-Major Axis (a) = 20381 km; Eccentricity, e, = 0.66; Inclination, I, = 63.435°

<u>Ground Track</u>	<u>Sat. No.</u>	<u>RAAN</u>	<u>ω</u>	<u>MA</u>
#1 (West. US)	VG1a	350	270	0
#1 (West. US)	VG2a	62	270	144
#1 (West. US)	VG3a	134	270	288
#1 (West. US)	VG4a	206	270	72
#1 (West. US)	VG5a	278	270	216
#2 (East. US)	VG1b	263.8	270	108.2
#2 (East. US)	VG2b	335.8	270	252.2
#2 (East. US)	VG3b	47.8	270	36.2
#2 (East. US)	VG4b	119.8	270	180.2
#2 (East. US)	VG5b	191.8	270	324.2
#3 (S.A., Australia)	VG1c	61	90	0
#3 (S.A., Australia)	VG2c	133	90	144
#3 (S.A., Australia)	VG3c	205	90	288
#3 (S.A., Australia)	VG4c	277	90	72
#3 (S.A., Australia)	VG5c	349	90	216

Although only a few embodiments have been described in detail above, other embodiments are contemplated by the inventor and are intended to be encompassed within the following claims. In addition, other modifications are contemplated and are also intended to be covered.

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